Development of Sustainable Corn Stover Harvest Strategies for Cellulosic Ethanol Production

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Abstract To prepare for a 2014 launch of commercial scale cellulosic ethanol production from corn/maize (*Zea mays* L.) stover, POET-DSM near Emmetsburg, IA has been working with farmers, researchers, and equipment dealers through "Project Liberty" on harvest, transportation, and storage logistics of corn stover for the past several years. Our objective was to evaluate seven stover harvest strategies within a 50-ha (125 acres) site on very deep, moderately well to poorly drained Mollisols, developed in calcareous glacial till. The treatments included the following: conventional grain harvest (no stover harvest), grain plus a second-pass rake and bale stover harvest, and single-pass grain plus cob-only biomass, grain plus vegetative material other than grain [(MOG) consisting of cobs, husks, and upper plant parts], grain plus all vegetative material from the ear shank upward (high cut), and all vegetative material above a 10 cm stubble height (low cut), with a John Deere 9750 STS combine, and grain plus direct baling of MOG with an AgCo harvesting system. Average grain yields were 11.4, 10.1, 9.7, and 9.5 Mg ha^{-1} for 2008, 2009, 2010, and 2011, respectively. Average stover harvest ranged from 0 to 5.6 Mg ha^{-1} and increased N, P, and K removal by an average of 11, 1.6, and 15 kg Mg^{-1}, respectively. Grain yield in 2009 showed a significant positive response to higher 2008 stover removal rates, but grain yield was not increased in 2010 or 2011 due to prior-year stover harvest. High field losses caused the direct-bale treatment to have significantly lower grain yield in 2011 because the AgCo system could not pick up the severely lodged crop. We conclude that decreases in grain yield across the 4 years were due more to seasonal weather patterns, spatial variability, and not rotating crops than to stover harvest.

Keywords Bioenergy · Sustainable feedstock production · Nutrient removal · Soil organic carbon

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Introduction

POET-DSM and two other commercial entities are preparing to launch three cellulosic ethanol conversion facilities in 2014. A core foundation for all three business models is the US EPA projection that corn stover, the aboveground material left in fields after grain harvest, will be "the most economical agricultural feedstock … to meet the 16 billion gallon cellulosic biofuel requirement" [1]. The EPA estimated that 7.8 billion gallons of ethanol would come from 82 million tons of corn stover by 2022, which is consistent with the conclusions reached by the US Department of Energy [2]. Stover harvest therefore has significant potential benefits as a bioenergy feedstock, and with appropriate site selection, its removal can help mitigate residue management problems in high-yielding cornfields [3]. However, stover harvest will increase nutrient removal [4, 5], and if an excessive amount is removed, its harvest could substantially decrease soil organic matter (i.e., soil organic carbon) and increase soil loss through increased wind and water erosion [6–8]. Therefore, for stover harvest to be sustainable, both the potential benefits and ecological consequences must be considered.

POET-DSM Advanced Biofuels is currently completing construction of a commercial scale plant near Emmetsburg, IA and expects to begin producing cellulosic ethanol from corn stover in 2014. For the past several years, POET-DSM has been working with farmers, researchers, and equipment dealers through "Project Liberty" to develop sustainable harvest, transportation, and storage logistics for corn stover. To quantify the impact of stover harvest on soil productivity, a multiyear cooperative research project at the Emmetsburg site was initiated in 2008. The objective of this study was to compare various corn stover harvest strategies to determine which would be the most sustainable and to evaluate the effect of stover harvest and removal on subsequent crop yields, soil fertility indicators, plant nutrient removal, and soil organic carbon (SOC) concentrations.

Materials and Methods

In 2008, a complete block design with 1.8-ha (4.4 acres) plots, replicated three times, was imposed on a 50-ha (125 acres) Clarion-Nicollet-Webster soil association at site near Emmetsburg, Iowa, USA. The Clarion series (fine-loamy, mixed, superactive, mesic Typic Hapludolls) consists of very deep, moderately well-drained soils on uplands. These soils formed in glacial till and have slopes ranging from 1 to 9 %. The Nicollet series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) consists of very deep, somewhat poorly drained soils that formed in calcareous loamy glacial till on till plains and moraines. Slopes range from 0 to 5 %. The Webster series (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) consists of very deep, poorly drained, moderately permeable soils formed in glacial till or local alluvium derived from till on uplands. Slope ranges from 0 to 3 %. Mean annual air temperature for all three series ranges from 8 to 9 ° C (47 to 48 ° F), and mean annual precipitation ranges from 660 to760 mm (28 to 30 in.).

The experiment included seven different treatments. Six were imposed with a John Deere 9750 STS[1] combine. Four of them utilized a "conventional" corn head: conventional grain harvest (no stover harvest), a multiple-pass rake and round bale stover harvest, cob only harvest, and collection of plant material other than grain (MOG). High-cut (just below the ear shank) and low-cut (10 cm stubble height) treatments required a "row-crop" head. The seventh treatment was a direct baling of MOG with an AgCo combine with attached baler. For the multiple-pass rake and round-bale treatment, standing stalks were shredded with a rotary cutter after conventional harvest, windrowed, and baled. All tillage and planting operations were carried out by a POET-DSM contractor. Annual tillage practices consisted of a fall chisel disking following harvest and one or two tillage passes with a field cultivator in the spring to prepare the seedbed.

Prior to machine harvest, total aboveground biomass production was estimated by collecting 2-m row length samples from each treatment plot. The plant material was segregated into four categories: top 50 % (all materials above the cob attachment location including husks), bottom 50 % (all materials below cob attachment location), cobs only, and hand-shelled grain mass. Except for 2008, plant material from the current crop that was on the ground (i.e., broken tassels, dropped leaves, etc.) was collected as a separate fifth fraction. All plant samples were dried, weighed, and used to estimate total aboveground biomass production. Plant samples were subsequently ground to pass a 0.5-mm screen. One subsample was analyzed by dry combustion to determine C and N concentrations, while another was digested with sulfuric acid and hydrogen peroxide before analyzing the material for P, K, Ca, Mg, Na, S, Al, B, Cu, Fe, Mn, and Zn concentrations using an inductively coupled plasma spectrophotometer (ICP).

Following harvest each autumn, several soil cores were collected randomly and composited for each plot. Samples were dried, crushed, and passed through a 2-mm screen before submitting them for analysis through a commercial laboratory. There, a subsample was analyzed for soil pH [9] and electrical conductivity (EC) [10] using a 1:1 soil to water ratio. A second subsample was analyzed for Bray-1 Extractable P (Bray P) [11] and ammonium-acetate (NH4OAc) exchangeable (Ex-) K, Ca, Mg, and Na concentrations [12]. A third subsample was extracted with diethylenetriaminepentaacetic acid (DPTA) [13] and analyzed using an ICP to determine Fe, Mn, and Zn concentrations. A fourth subsample was extracted with 2 mol L^{-1} KCl and analyzed using a flow injection analyzer (Lachat Instruments, Loveland, CO) to determine NO_3–N concentration. A fifth subsample was analyzed for B by ICP after extracting the soil with a 0.005 M DTPA–0.2 M sorbitol solution (1:2 soil/solution ratio) as described by Miller et al. [14]. Finally, a sixth subsample was extracted with calcium phosphate [15] and analyzed to determine plant available S concentrations.

A portion of each soil sample was retained and analyzed by the ARS National Laboratory for Agriculture and the Environment (NLAE) analytical laboratory for total nitrogen (TN) and total carbon (TC) concentrations. For samples with pH values greater than 7.2, inorganic C (IC) was also determined as outlined by Wagner et al. [16]. SOC values were then calculated as the difference between TC and IC with the latter being considered zero for samples with pH<7.2.

Grain and stover yield data, plant nutrient concentrations, and soil-test values were analyzed using SAS statistical software (SAS Institute, Cary, NC).

Results and Discussion

Average machine-harvested grain yields were 11.4, 10.1, 9.7, and 9.5 Mg ha^{-1} for 2008, 2009, 2010, and 2011, respectively

[1] Mention of a specific product or proprietary name is for reference only and does not constitute preference or endorsement by Iowa State University or the USDA-Agricultural Research Service (ARS).

(Table 1). Among the seven stover management treatments, the 4-year averages show that the only significant difference (α=0.05) was between the low-cut and direct-bale treatments. Presumably, this was the result of the low direct-bale grain yields in 2011 as discussed below. Among the years, the lack of differences in 2008 was expected and desirable since there had been no stover harvest treatments imposed on the 2007 corn crop. In 2009, grain yields were lower than in 2008, ranging from 9.6 to 10.7 Mg ha^{-1} with an average of 10.1 Mg ha^{-1}. Plots with higher stover removal rates in 2008 (i.e., low-cut, high-cut, and two-pass baling at 4.9, 4.7, and 5.2 Mg ha^{-1}, respectively) had grain yields in 2009 that were 0.8, 0.9, and 0.7 Mg ha^{-1} (12, 14, and 11 bu acre^{-1}) higher than those from conventional plots (i.e., zero removal). However, with lower stover removal rates in 2008 (i.e., cobs only and MOG removal at 1.1 and 1.6 Mg ha^{-1} (0.5 and 0.7 tons acre^{-1}), 2009 grain yields were not significantly different from those with conventional management. In 2010, grain yields were even lower than in previous years due to the significant early season ponding in the field and possible nutrient stress. Grain yields that year ranged from 8.8 to 11.1 Mg ha^{-1} (140 to 178 bu acre^{-1}), with a mean for the seven treatments of 9.7 Mg ha^{-1} (155 bu acre^{-1}). With regard to the stover harvest treatments, the 2010 grain yield response was similar to that observed in 2009, with the high-removal treatment (i.e., low-cut at 5.6 Mg ha^{-1} or 2.5 tons acre^{-1}) yielding on average 1.6 Mg ha^{-1} (25 bu acre^{-1}) more than the conventional (i.e., zero removal) treatment. In 2011, grain yields were further depressed for all stover harvest treatments, ranging from 8.3 to 9.9 Mg ha^{-1} (132 to 159 bu acre^{-1}) and having a mean value of 9.5 Mg ha^{-1} (151 bu acre^{-1}). We attribute this decline primarily to a localized, high-wind event on August 23, 2011 that caused significant lodging throughout the entire field. The lodging, which occurred before the crop reached physiologic maturity, made combining the crop later that year very difficult and resulted in a substantial amount of grain being left in the field as a "harvest loss." The grain loss associated with the direct-bale treatment resulted in an even higher than normal yield variability throughout the field. Therefore, the 2011 grain yield response to prior stover harvest treatments was statistically nonsignificant (α=0.05), except for the direct-bale treatment, which, as stated, is attributed to using a different combine for those plots.

Overall, we attribute the 4-year grain yield decline more to the well-known yield penalty associated with continuous corn production [17], variability in soil fertility across the 125-ha field, excessive early season rainfall in 2010, and severe wind damage in August 2011 than to any of the stover harvest treatments. However, when mean grain yields (Table 1) are compared on a relative basis by dividing each treatment mean by the conventional yield, values for the various treatments range from 93 to 107 %. Again, we emphasize that statistically there were no significant differences in grain yield between the conventional (no removal) and low-cut treatments when averaged for the 4 years, but harvesting an average of 5.6 Mg ha^{-1} year^{-1} (2.5 tons acre^{-1} year^{-1}) of residue did increase grain yield by 7 % (i.e., 0.6 Mg ha^{-1} or 10 bu acre^{-1}). Similar relative yield comparisons for each of the 4 years

Table 1 Average machine-harvested and relative corn grain yields as affected by various stover collection methods near Emmetsburg, Iowa, USA

Treatment	Grain yield (Mg ha^{-1})					Relative yield
	2008	2009	2010	2011	Average	
Conventional	11.3a[a]	9.8ab	9.5a	9.9a	10.1ab	1.00
Cobs only	11.2a	9.6a	9.5a	9.9a	10.0ab	0.99
MOG	11.7a	9.6a	9.6a	9.9a	10.2ab	1.00
Direct baling[b]	–	10.3abc	9.7a	8.3b	9.4a	0.93
High-cut (~50 %)	11.2a	10.7c	8.8a	9.4a	10.0ab	0.99
Two-pass baling	11.1a	10.5bc	9.8a	9.3a	10.2ab	1.00
Low-cut (~90 %)	11.8a	10.6bc	11.1a	9.7a	10.8b	1.07
Average	11.4a	10.1b	9.7c	9.5c	10.2	

Letters associated with the average values are not to be compared with those in the column above, but rather used for comparisons among the 4 years

[a] Treatment values within a column followed by the same letter are not statistically different at α=0.05

[b] Grain harvest and direct baling of corn stover were accomplished using an AgCo harvest system. Grain from all other treatments was harvested with a John Deere 9750 STS combine. Except for the two-pass baling treatment for which the stover was collected in a separate operation, the cobs only, MOG, high-cut, and low-cut stover collections were accomplished using the modified 9750 STS combine

Table 2 Average machine-harvested stover yield and percent collected as affected by stover collection method near Emmetsburg, Iowa, USA

Treatment	Stover yield (Mg ha^{-1})				
	2008	2009	2010	2011	Average
Conventional	–	–	–	–	–
Cobs only	1.1c[b]	1.6e	1.1c	0.4d	1.1e
MOG	1.6b	2.0d	1.3c	1.8c	1.6d
Direct baling[a]	–[c]	2.0d	1.8c	2.5c	2.0c
High-cut (~50 %)	4.7a	4.0b	3.8b	4.9b	4.3b
Two-pass baling	5.2a	3.4c	3.1b	6.5a	4.5b
Low-cut (~90 %)	4.9a	5.6a	5.6a	6.0a	5.6a

[a] Grain harvest and direct baling of corn stover were accomplished using an AgCo harvest system. Grain from all other treatments was harvested with a John Deere 9750 STS combine. Except for the two-pass baling treatment for which the stover was collected in a separate operation, the cobs only, MOG, high-cut, and low-cut stover collections were accomplished using the modified 9750 STS combine

[b] Treatment values within a column followed by the same letter are not statistically different at α=0.05

[c] The direct-baling equipment was not available in 2008. Plots used for subsequent years were managed conventionally with no stover harvest

show that the low-cut treatment grain yields were 105, 108, 117, and 98 % of the conventional harvest treatment in 2008, 2009, 2010, and 2011, respectively.

Two factors are presumably responsible for the higher yield trend associated with the low-cut plots—namely higher early season soil temperature which hastens seed germination and less immobilization of plant available N due to less carbon being available for microbes to decompose. The hypothesis that there was less N immobilization following stover harvest can be supported by observations from other Renewable Energy Assessment Project (REAP) team studies near Ames, IA, but measurable soil temperature effects are less certain and warrant further study at this and other locations. Finally, we caution that the relative yield increase observed with high rates of stover removal may not be sustainable in the long term due to nutrient mass balance and the need for soil organic carbon to maintain good aggregate structure, infiltration, retention, and release of plant available water. This recommendation is supported by many studies in this special issue and elsewhere documenting adverse soil resource effects of

Fig. 1 Postharvest soil surface cover for various stover collection strategies evaluated near Emmetsburg, Iowa, USA

depleting soil organic matter (i.e., soil carbon) due to excessive biomass removal.

With the impending launch of the POET-DSM cellulosic ethanol plant in 2014, the need for grain yield and available stover estimates will continue to increase. One method to obtain that information would be to collect random yield samples by hand from various locations within a field and then estimate stover production using a 1:1 dry grain to dry stover ratio. Comparisons between 2-m row length, hand-harvested grain yield estimates, and grain yields measured with the combine for 2008 show that hand-sample yields ranged from 11.3 to 12.5 Mg ha^{-1} (180 to 200 bu acre^{-1}) with an average of 11.9 Mg ha^{-1} (189 bu acre^{-1}) which was slightly higher but consistent with the combine grain yields (Table 1). In 2009, the hand-sample grain yield estimates ranged from 8.6 to 9.5 Mg ha^{-1} (137 to 152 bu acre^{-1}) with an average yield of 9.2 Mg ha^{-1} (146 bu acre^{-1}). This was slightly lower than the yields measured with the combines. In 2010, hand-harvested yields ranged from 9.6 to 12.0 Mg ha^{-1} (153 to 191 bu acre^{-1}) with an average yield of 10.8 Mg ha^{-1} (173 bu acre^{-1}), which was once again slightly higher than the yield levels measured with the combines. However, in 2010, there was significant ponding at lower elevation areas within the plots, which reduced overall plot yields. These random, low-yield areas were avoided when collecting the hand samples, thus contributing to the higher potential yield estimates. Finally, in 2011, the hand-harvested grain yield estimates ranged from 9.3 to 13.7 Mg ha^{-1} (149 to 218 bu acre^{-1}) with an average of 12.2 Mg ha^{-1} (194 bu acre^{-1}), which was much higher than the grain yields measured with the combines. The 2011 machine-harvested grain yields were much lower than the hand-harvested estimates due to significant lodging caused by the high-wind event in August. That storm caused over 50 % of the field to be severely lodged and contributed to substantial harvest losses during the combining operations. These results emphasize that if hand samples are used to estimate potential grain yields and available stover supplies, care should be taken to collect a sufficient number of samples to accurately represent all field areas where stover harvest might occur.

Over the 4 years, the average, machine-collected biomass yield was 5.6, 4.5, 4.3, 1.6, 2.0, and 1.1 Mg ha^{-1} (2.5, 2.0, 1.9, 0.7, 0.9, and 0.5 tons acre^{-1}) for the low-cut, two-pass baling, high-cut, MOG, single-pass baling, and cob only harvest strategies, respectively (Table 2). Stover moisture content for the machine-harvested material ranged from 93 g kg^{-1} in the cob and MOG treatments to 350 g kg^{-1} for the low-cut treatment. Hand-harvested cob yields ranged from 1.1 to 2.3 Mg ha^{-1} (0.50 to 1.04 tons acre^{-1}), with an average of 1.6 Mg ha^{-1} (0.70 tons acre^{-1}), while total stover yield estimates ranged from 7.3 to 8.2 Mg ha^{-1} (3.27 to 3.64 tons acre^{-1}), with an average of 8.1 Mg ha^{-1} (3.63 tons acre^{-1}). This means that on average, cob mass accounted for 20 % of the aboveground biomass which is consistent with other studies [18]. The hand-collected samples also provided data needed to calculate harvest index (HI) values, which indicate the quantity of harvestable biomass per unit total biomass produced. Values at this site ranged from 0.48 to 0.64 and averaged 0.57. The impact of having HI values that are greater than 0.50 is that the 1:1 dry corn grain to

Table 3 Average machine-harvested stover constituent analysis as affected by stover collection method near Emmetsburg, Iowa, USA

Treatment	Stover nutrient concentrations							
	C	N	P	K	Ca	Mg	S	Na
	g kg^{-1}							
Cobs only	451a[a]	4.4c	0.58a	6.8a	1.4c	0.8c	0.48a	0.33a
MOG	446ab	4.6bc	0.61a	6.8a	1.6c	0.8c	0.54a	0.35a
Direct baling	442ab	5.4a	0.70a	8.6a	2.0c	1.1bc	0.36a	0.11a
High-cut (~50 %)	443ab	5.3ab	0.82a	8.6a	2.8b	1.6ab	0.57a	0.33a
Two-pass baling	412c	5.6a	0.77a	7.1a	3.9a	2.0a	0.58a	0.33a
Low-cut (~90 %)	437b	5.7a	0.84a	7.9a	3.4ab	2.0a	0.56a	0.33a
Average	438	5.2	0.73	7.6	2.5	1.4	0.52	0.30
	Al	B	Cu	Fe	Mn	Zn		
	mg kg^{-1}							
Cobs only	24b	5.6d	2.7b	43b	12.5d	16.7a		
MOG	22b	6.3 cd	2.6b	44b	17.6 cd	20.1a		
Single-pass baling	33b	6.1 cd	3.5ab	86b	22.5bc	19.1a		
High-cut (~50 %)	27b	6.6bc	3.6ab	56b	23.6bc	13.2a		
Two-pass baling	531a	8.1a	4.2a	702a	50.3a	14.2a		
Low-cut (~90 %)	43b	7.2b	3.5ab	81b	28.1b	13.6a		
Average	118	6.7	3.4	174	26.0	16.0		

[a] Values within any column followed by the same letter are not significantly different (α=0.05)

Table 4 Four-year average postharvest soil-test values within the 15-cm surface as affected by stover collection method near Emmetsburg, Iowa, USA

Treatment	pH	OC	IC	NO_3–N	P	K	Ca	Mg	Na	S	B	Fe	Mn	Zn
		g kg^{-1}		mg kg^{-1}										
Conventional	6.9	31.9	3.8	10.1	25	169	5,369	412	10	8.2	0.8	53a[a]	6.8	1.7
Cobs only	6.9	32.4	3.5	9.8	30	169	5,275	413	11	8.3	0.7	55a	5.7	1.2
MOG	6.9	31.4	2.8	8.8	28	172	5,141	411	10	7.2	0.7	47ab	5.3	1.3
Direct baling	7.2	31.9	2.8	10.3	23	162	4,983	392	10	6.8	0.7	36bc	3.7	1.7
High-cut (~50 %)	7.1	31.2	3.5	8.5	20	166	5,523	428	10	7.3	0.6	31c	4.2	1.2
Two-pass baling	6.9	31.2	2.5	10.1	26	169	5,130	438	11	7.8	0.7	50a	6.6	2.0
Low-cut (~90 %)	7.1	33.0	3.8	8.8	27	172	5,767	402	10	7.6	0.7	44abc	5.4	1.0

Mean values followed by the same letter are not significantly different at α=0.05

OC organic carbon, *IC* inorganic carbon, *NO_3–N* nitrate nitrogen, *P* phosphorus, *K* potassium, *Ca* calcium, *Mg* magnesium, *Na* sodium, *S* sulfur, *B* boron, *Fe* iron, *Mn* manganese, *Zn* zinc

[a] Iron was the only element for which significant differences were noted, and these are assumed to be driven by spatial variation within the field rather than a true stover harvest treatment effect

dry stover ratio is no longer valid, and therefore, there is less potentially available aboveground biomass to harvest in a sustainable manner. The key to managing for high HI values is to utilize best management practices to increase yields and thus provide sufficient stover to sustain soil resources and provide bioenergy feedstock. Protection of the soil surface from wind and water erosion is another critical ecological service provided by crop residues in general, and specifically by corn stover. Figure 1 provides a visual illustration of the residual surface cover associated with the low-cut, multiple-pass rake and bale, high-cut, MOG, cob only, and conventional grain harvest treatments, respectively. Specific soil surface cover percentages associated with various stover harvest strategies are now being measured at this location and in other REAP studies, but that data was not collected during the first 4 years of research at this location.

Increased nutrient removal and the need to replace them through increased fertilizer application rates is another concern associated with developing sustainable corn stover feedstock supplies for any bioenergy or bio-product industry. Measurements in samples from this site show that stover nutrient concentrations were highly correlated to the percentage of lower stalk that was collected (Table 3). For example, the N concentration increased from 4.4 g kg^{-1} in cob only samples to 5.7 g kg^{-1} in low-cut samples that left only 10 cm of stubble in the field. This difference was statistically significant at α=0.05. Plant P and K concentrations also increased as a higher percentage of the lower plant parts were collected, but those differences were not statistically significant at the 5 % probability level. These subtle but consistent changes in nutrient concentration are caused by a translocation of nutrients from upper plant parts to lower stems and roots as plant senescence occurs.

Increased nutrient removal associated with stover harvest is calculated based on the amount removed and the appropriate nutrient concentration of the fraction harvested. Average values for this study show that N removal per metric ton (megagram) of biomass ranged from 10 to 14 kg Mg^{-1} (9 to 12 lb ton^{-1}) for the cob only and low-cut harvest strategies, respectively, and averaged 11 kg Mg^{-1} (10 lb ton^{-1}) for all treatments. Increases in P removal per megagram of biomass ranged from 1.3 to 1.8 kg Mg^{-1} (1.2 to 1.6 lb ton^{-1}) for the cob only and low-cut strategies, respectively, with an average of 1.6 kg Mg^{-1} (1.4 lb ton^{-1}) for all harvest strategies. Similarly, K removal was increased by 14 to 15 kg Mg^{-1} (12 to 13.6 lb ton^{-1}) for cobs only and low-cut treatments,

Table 5 Yearly postharvest soil-test values within the 15-cm surface when averaged across seven stover harvest treatments evaluated near Emmetsburg, Iowa, USA

Year	pH	OC	IC	NO_3–N	P	K	Ca	Mg	Na	S	B	Fe	Mn	Zn
		g kg^{-1}		mg kg^{-1}										
2008	6.9bc[a]	34.3a	–	4.7d	33a	191a	6,246a	545a	–	–	–	37b	9a	0.4b
2009	7.1ab	31.1b	4.7a	9.3c	24bc	156b	5,081b	390b	7c	6.7b	0.7b	43ab	2b	0.5b
2010	7.2a	30.5b	2.9b	12.7a	19c	147b	4,563c	333c	10b	8.0a	0.4c	43ab	3b	3.8a
2011	6.8c	31.6b	2.2b	10.5b	28ab	183a	5,541b	408b	14a	8.2a	0.9a	59a	8a	0.8b

OC organic carbon, *IC* inorganic carbon, *NO_3–N* nitrate nitrogen, *P* phosphorus, *K* potassium, *Ca* calcium, *Mg* magnesium, *Na* sodium, *S* sulfur, *B* boron, *Fe* iron, *Mn* manganese, *Zn* zinc

[a] Values within any column followed by the same letter are not significantly different (α=0.05)

respectively, with an average of 15 kg Mg^{-1} (13 lb ton^{-1}) for all treatments.

Our final sustainability assessment focused on soil-test values during the course of the study. Those analyses showed substantial field variability but no significant stover harvest treatment effects (Table 4) at α=0.05. Among the three replicates, however, there were significant differences for all parameters except Mg, Zn, S, Na, and inorganic carbon. Soil organic carbon and pH showed substantial variation among replicates, reflecting spatial variation in topography, soil type, and residual fertility levels across the field (data not presented). Finally, when soil-test values were compared across years (Table 5), there was significant variation in all parameters. There was also a slight but statistically significant decrease in soil organic carbon, but we suggest that this was due more to the intensity of tillage and lower than expected crop yields due to weather and other factors than to any of the stover harvest treatments. Our long-term goal based on these analyses is to use site-specific nutrient management and crop rotation to increase yields and to perhaps reduce tillage intensity by harvesting sustainable but sufficient quantities of stover to mitigate nutrient immobilization or other challenges currently pushing local producers to insist on using very aggressive tillage practices each year.

Summary and Conclusions

In summary, the first 4 years of research at this site showed minimal effects on grain yield, stover composition, and soil-test parameters due to the various stover harvest treatments. Spatial and seasonal variabilities were by far the most influential factors affecting both parameters. This emphasizes the importance of developing and maintaining a routine soil fertility testing and nutrient management program, before harvesting crop residues for any purpose. Failing to do so could serve as a tipping point that could ultimately reduce crop yields and degrade soil resources.

Overall, this project has shown that with good soil and crop management practices, corn yields should be sufficient to support a sustainable corn stover harvest of 1 Mg ha^{-1} (1 ton acre^{-1}) from this and similar fields. If management practices can be improved such that grain yields are consistently greater than 12.5 Mg ha^{-1} (200 bu acre^{-1}), it may even be possible to sustainably harvest even higher amounts of stover. Furthermore, by implementing subfield, site-specific management practices within individual fields, it may be feasible to increase average stover harvest even more. However, higher stover removal rates should never be considered or implemented if routine soil-test assessments indicate soil organic carbon is decreasing or grain yields are not being maintained.

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